# Heavy Diboson Production at the Tevatron

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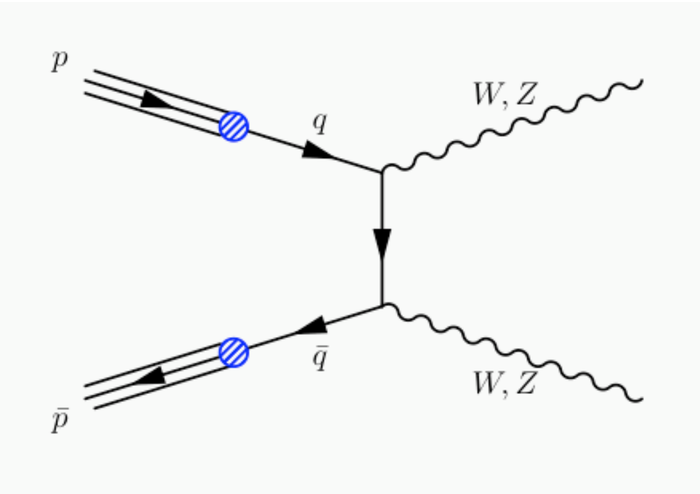
**on behalf of the CDF & DØ Collaborations**

- What are we Measuring & Why ?
- WW and WZ Production
- Anomalous Couplings
- First Measurement of ZZ Production
- Summary

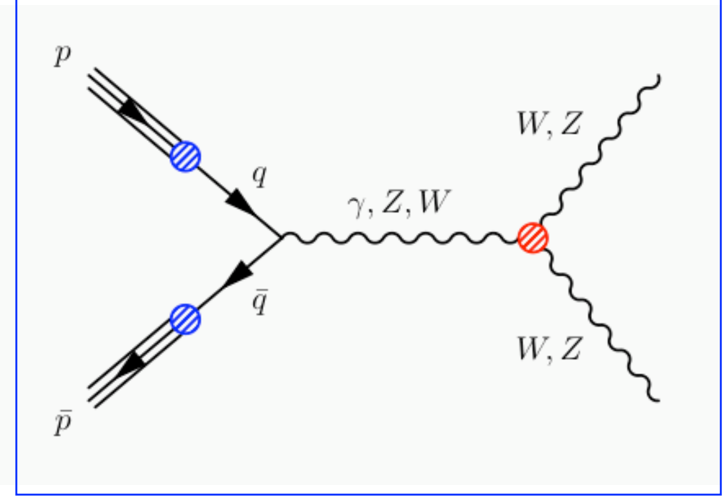
# Heavy Diboson Production at the Tevatron

Leading order diagrams :

**t**-channel




**s**-channel

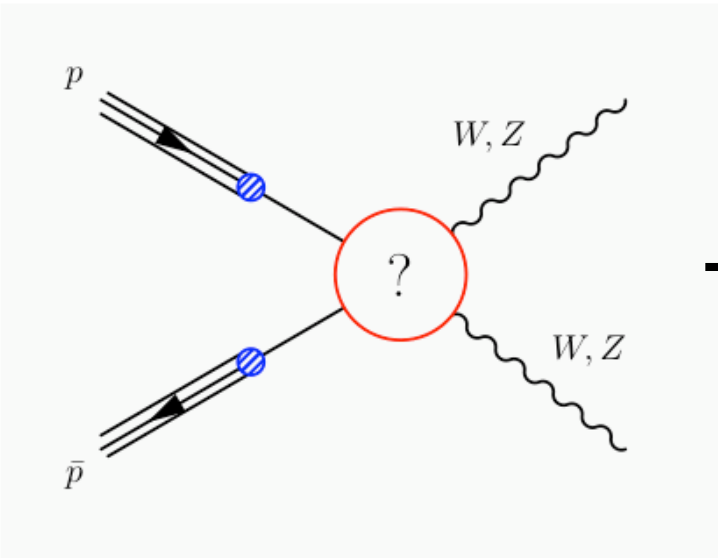



- (QCD) production : PDF's, (NLO/LO) k-factors, diboson-$p_T$ spectrum.
- (EWK) production : Triple Gauge Couplings predicted by **$SU(2)_L \otimes U(1)_Y$**.

- Measuring the production cross sections and kinematics provide a verification of all these production model ingredients.

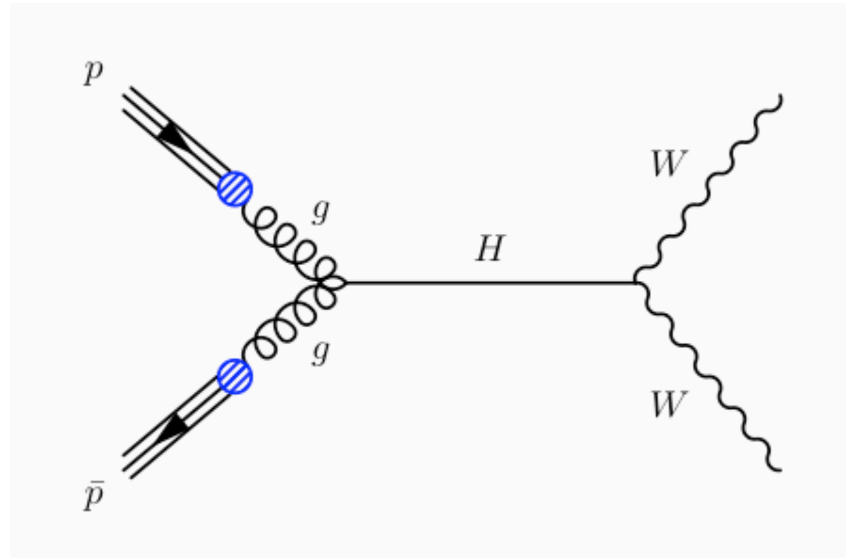
# Heavy Diboson Production at the Tevatron

- Heavy diboson production as a signature of new physics :




for

example

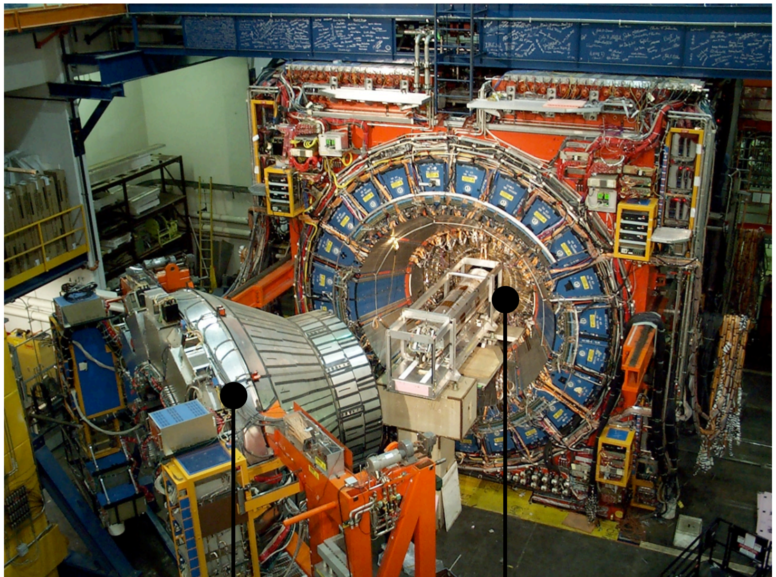



- Indeed, heavy diboson production is intimately related to Higgs searches:
  - **WW** production is a (quasi-) irreducible background to **H→WW**
  - **WZ and ZZ** production are critical backgrounds to **WH** & **ZH** assoc. prod.
  - Technically many of the techniques developed for diboson measurements have applications in Higgs searches.
  - Heavy diboson measurements provide a "standard-candle" for the measurement of very small cross sections.

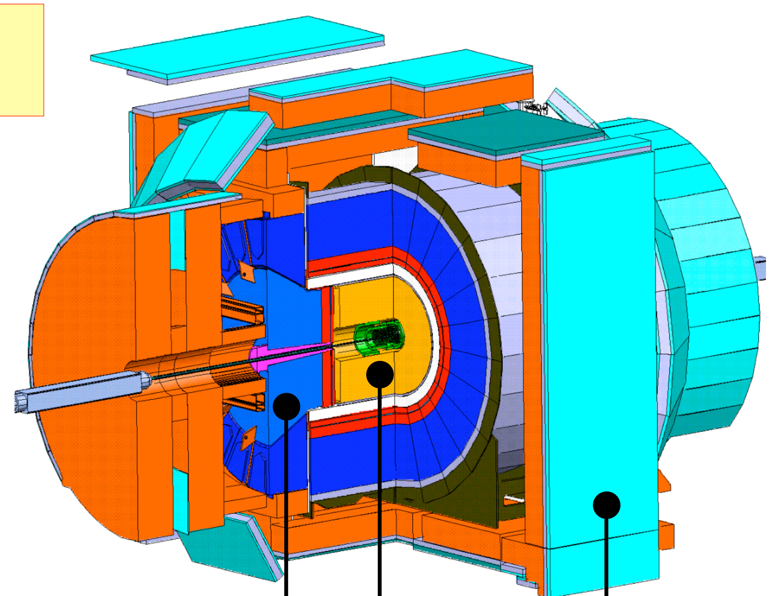
# Overview of Channels

| Channel | Events/Experiment in $1fb^{-1}$ | Signal/ Background | Significance of Observation (Gaussian $\sigma$ equivalent) |
|---|---|---|---|
| $WW \to l\nu l\nu$ | 580 | ~2 | >> 5 |
| $WW/WZ \to l\nu jj$ | 4100 | ~0.01 | ~1.7 |
| $WZ \to l\nu ll$ | 50 | ~2-4 | > 5 |
| $ZZ \to llll$ | 6 | ~10-20 | 4.4 |
| $ZZ \to ll\nu\nu$ | 40 | ~0.05-0.25 | |

# CDF Detector



**DØ detector : previous talk**



**Drift chamber outer tracker :**
$\delta p_T / p_T \approx 0.0005 \times p_T$ [GeV/c; beam constrained]; $|\eta| < 1$

**Silicon vertex detector :**
tracking coverage out to $|\eta| < 2.8$

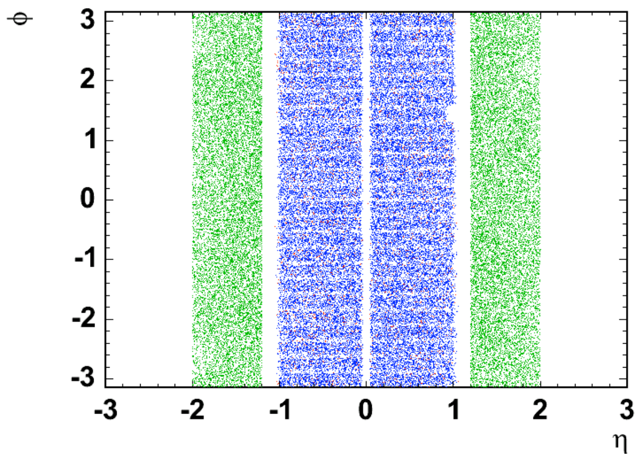
**Central calorimeter :** $\delta E_T / E_T \approx 13.5\% / \sqrt{E_T} \oplus 1.5\%$ $|\eta| < 1.1$

**Plug calorimeter :** coverage out to $|\eta| < 3.0$

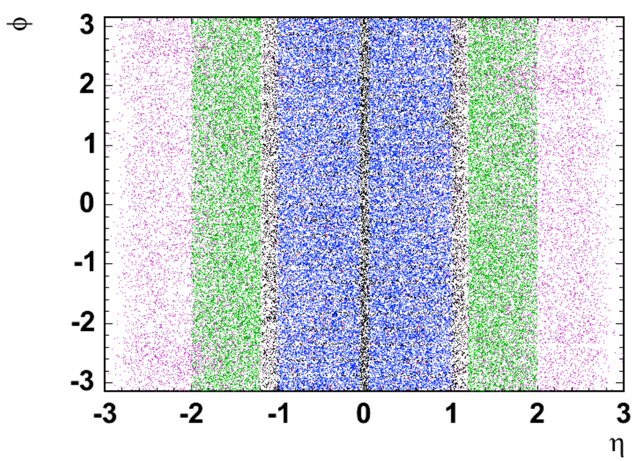
**Muon chambers :** coverage out to $|\eta| < 1.0$

# Optimising Sensitivity

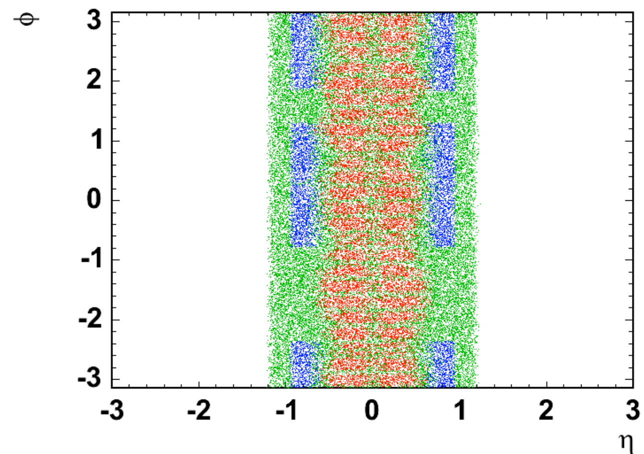
- Major technical advance : maximise single-lepton acceptance.



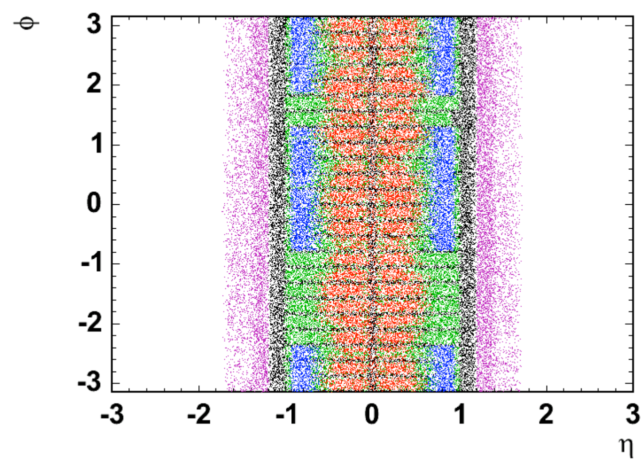

CDF Electron Coverage




forward leptons,
track only leptons




CDF Muon Coverage



# WW

- First observed by DØ and CDF in 2004 in ~200 $pb^{-1}$ samples.

PRL 94, 211801
PRL 94, 151801

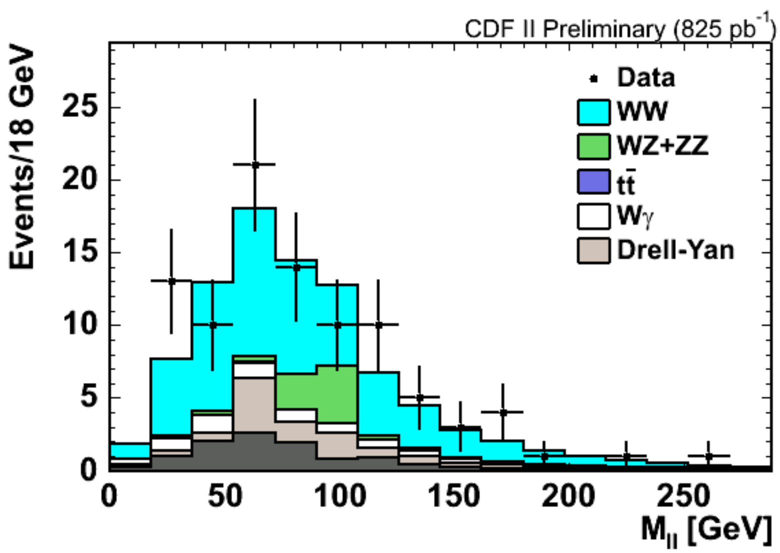
- **DØ (240 $pb^{-1}$)** : 25 candidates, expected background ~8

$$\sigma(WW) = 13.8^{+4.3}_{-3.8}\ (\text{stat.})\ ^{+1.2}_{-0.9}\ (\text{syst.}) \pm 0.9\ (\text{lumi.})\ \text{pb}$$

$$[\sigma_{NLO}(WW) = 12.4 \pm 0.8\ \text{pb}]$$

- **CDF (update using 825 $pb^{-1}$)** : 95 candidates, expected background ~38

$$\sigma(WW) = 13.6 \pm 2.3\ (\text{stat.}) \pm 1.6\ (\text{syst.}) \pm 1.2\ (\text{lumi.})\ \text{pb}$$




- Well understood samples.
- Starting point for H→WW searches.

# WZ

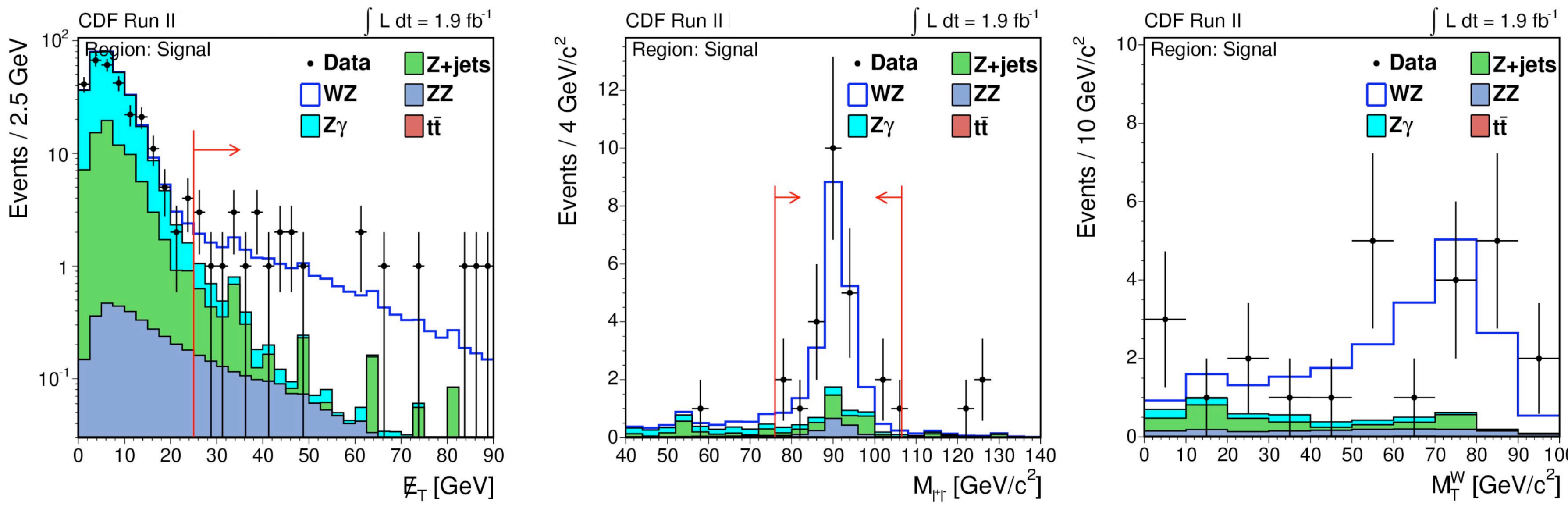
- First observed in 2006 in ~1 $fb^{-1}$ samples.
- Recent updates in tri-lepton channel :
  - **DØ (1 $fb^{-1}$)** : 13 candidates against expected background of 4.5 ± 0.6

$$\sigma(WZ) = 2.7\,^{+1.7}_{-1.3}\ \text{(stat. + syst.) pb} \qquad [\sigma_{NLO}(WZ) = 3.7 \pm 0.3\ \text{pb}]$$

  - **CDF (1.9 $fb^{-1}$)** : 25 candidates against expected background of 4.7 ± 0.8 :

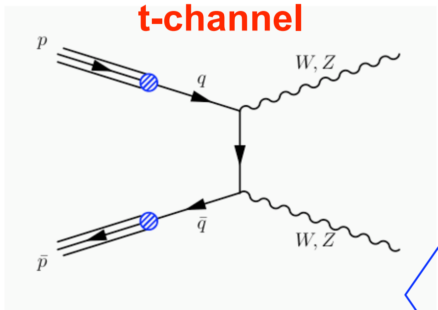
$$\sigma(WZ) = 4.4\,^{+1.3}_{-1.0}\ \text{(stat.)} \pm 0.2\ \text{(syst.)} \pm 0.3\ \text{(lumi.) pb}$$

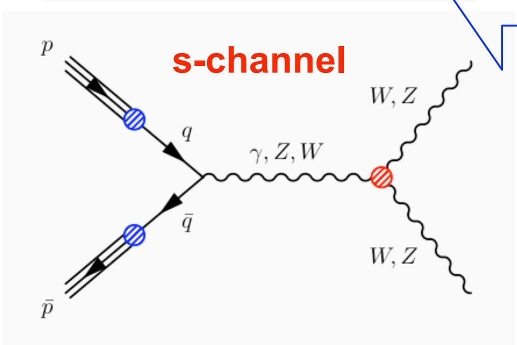
PRD 76, 111104(R)
PRL 98, 161801



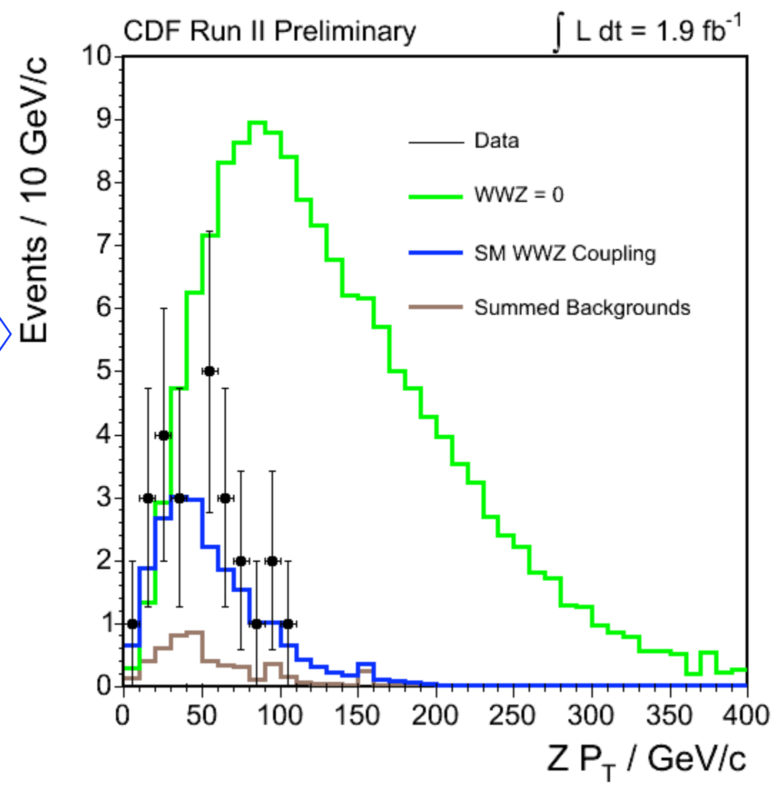
# WWZ Anomalous Couplings

- WZ production probes WWZ vertex independent of WWγ (cf. LEP2).



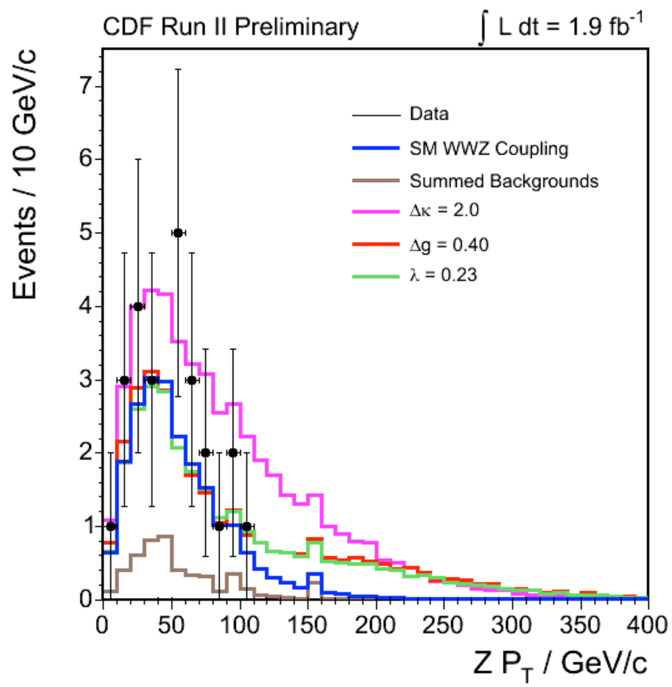



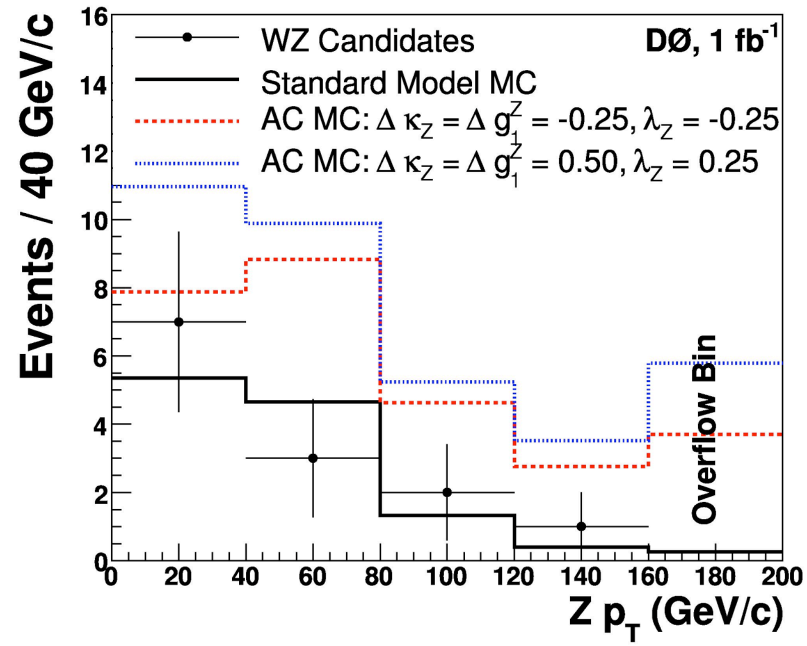

destructive interference in SM (that's why diboson cross sections are so small !)




- $p_T$(Z) is the kinematic observable most sensitive to anomalous WWZ couplings.

# WWZ Anomalous Couplings



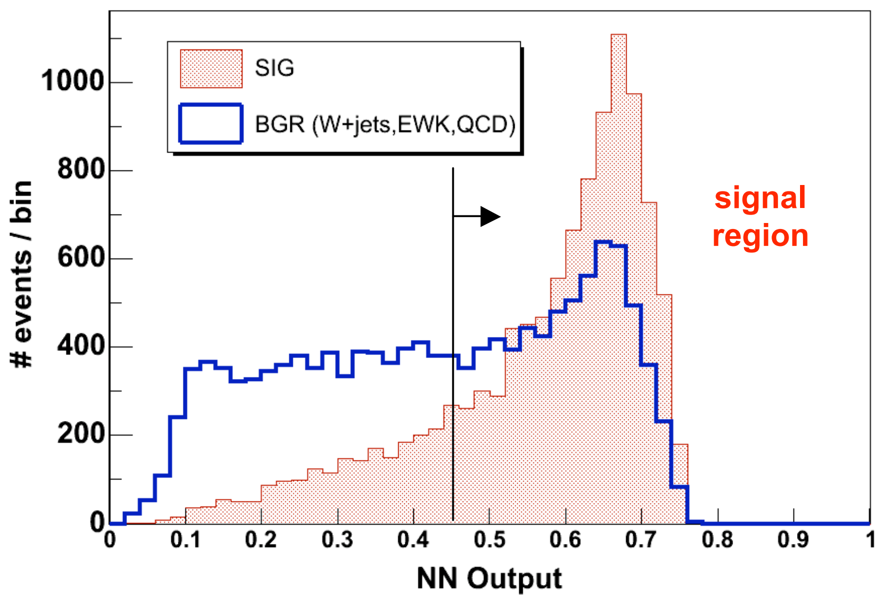

| 95% Confidence Level Intervals for $\Lambda$=2 TeV (*) | |
|---|---|
| CDF (1.9 fb$^{-1}$) | D$\varnothing$ (1.0 fb$^{-1}$) |
| $-0.13 < \lambda_Z < 0.14$ | $-0.17 < \lambda_Z < 0.21$ |
| $-0.13 < \Delta g_1^Z < 0.23$ | $-0.14 < \Delta g_1^Z < 0.34$ |
| $-0.76 < \Delta\kappa_Z < 1.18$ | $-0.12 < \Delta\kappa_Z = \Delta g_1^Z < 0.29$ |

(*) AC definitions as per Hagiwara et al. 1987

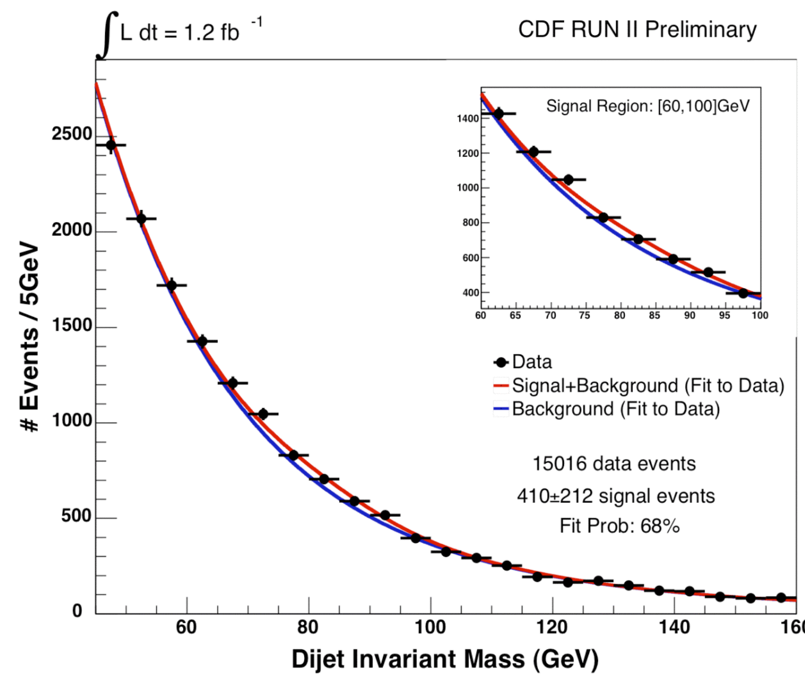
# WW/WZ→lνjj (CDF)

- Very challenging experimentally :
  - 5-10 × more signal compared to fully leptonic channels
  - 1000 × more background (S/B ~ 1%)
  - Similar final state to WH→lνjj
  - Potentially greater sensitivity to anomalous couplings

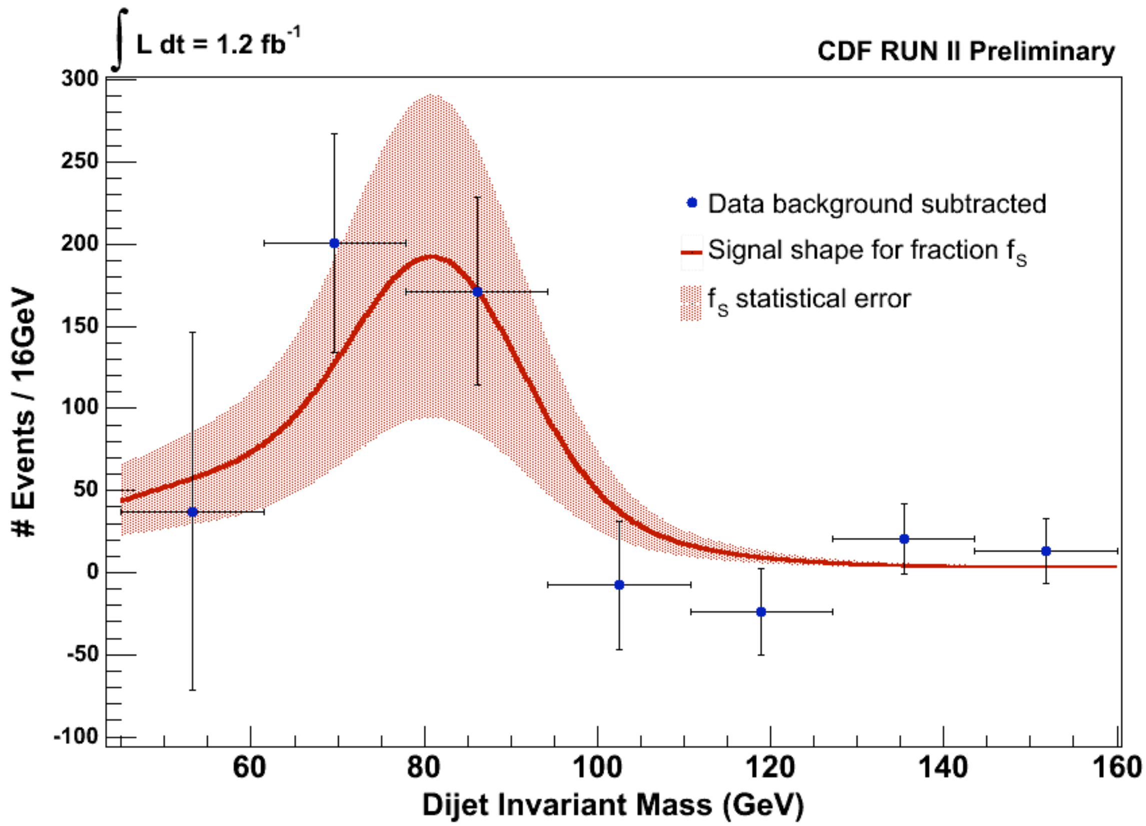
**(I)** Train a neural network using dimensionless event shape variables :




**(II)** Then fit $m_{jj}$ distribution :



# WW/WZ→lνjj (CDF)




| | |
|---|---|
| $N_{signal}$ | 410 ± 212 (stat) ± 107 (syst) pb |
| **Observed** | **$\sigma \times$ BR = 1.47 ± 0.77 (stat) ± 0.38 (syst) pb** |
| **95% Limit** | $\sigma \times$ BR < 2.88 pb |
| **NLO Prediction** | $\sigma \times$ BR = 2.09 ± 0.14 pb |

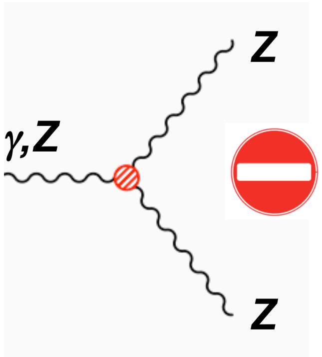
# ZZ→llll (DØ)

- 4-lepton final state has very low backgrounds (mainly Z+jets).
- Wide mass range $m_{ll}$>30 GeV/$c^2$ includes Z/$\gamma^*$.

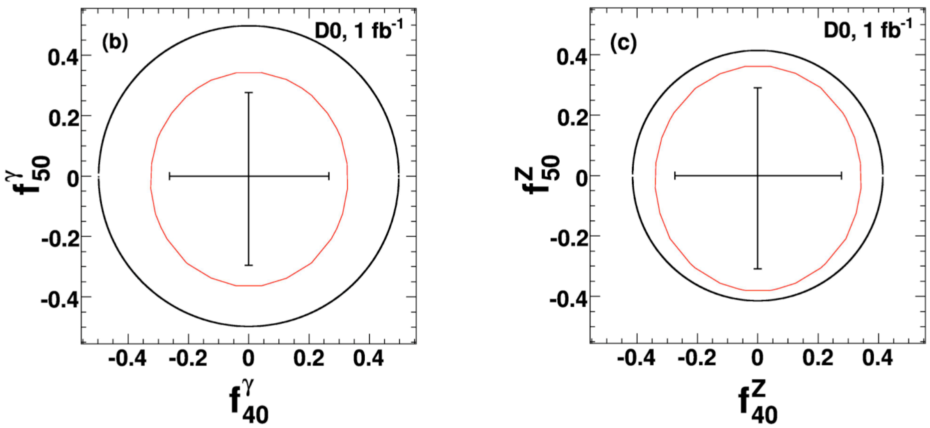
| 1 $fb^{-1}$ | eeee | ee$\mu\mu$ | $\mu\mu\mu\mu$ | Total |
|---|---|---|---|---|
| **ZZ** | 0.44±0.03 | 0.81±0.09 | 0.46±0.05 | 1.71±0.15 |
| **Background** | 0.080±0.021 | 0.013±0.004 | 0.033±0.006 | 0.13±0.03 |
| **Data** | **0** | **1** | **0** | **1** |

**$\sigma$(ZZ) < 4.4 pb [$\sigma_{NLO}$(ZZ) = 1.6 pb]**

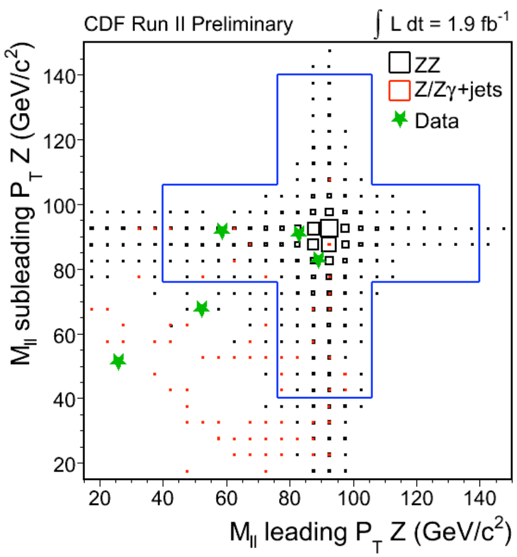
- No s-channel contribution to ZZ production at LO in the Standard Model.
- Tighter mass cuts to define resonant Z's.
- Zero events → set AC limits.




ZZ$\gamma^*$ ($\Lambda$=1.4 TeV) ZZZ

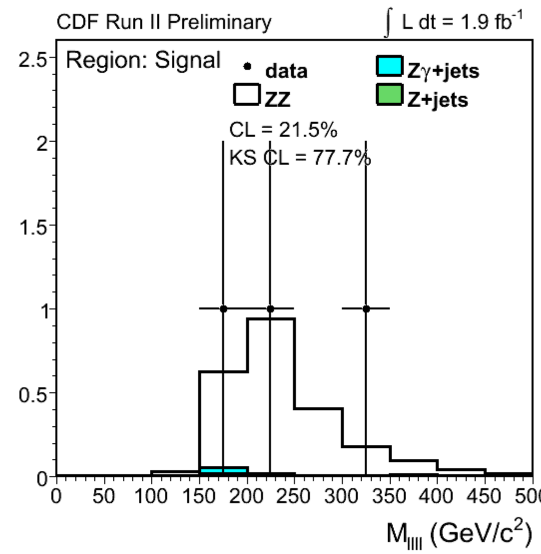


# ZZ→llll (CDF)




Mass range $m_{ll} \in$ [76,106] and [40,140] GeV/$c^2$ to include Z/γ*.

Very small backgrounds from Z(γ)+jets

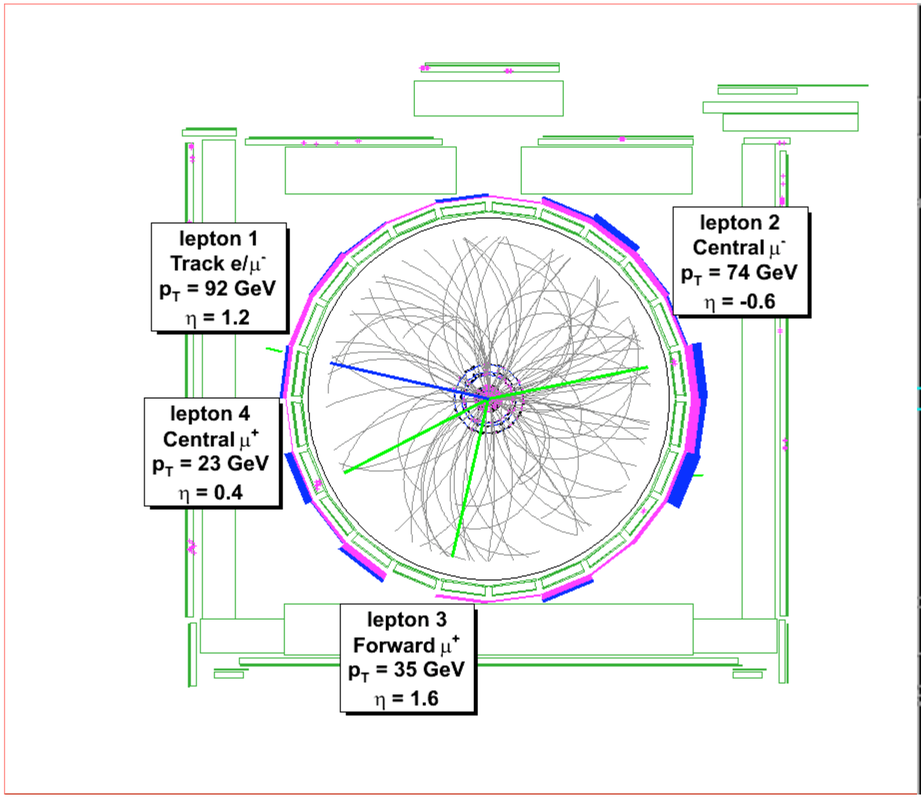


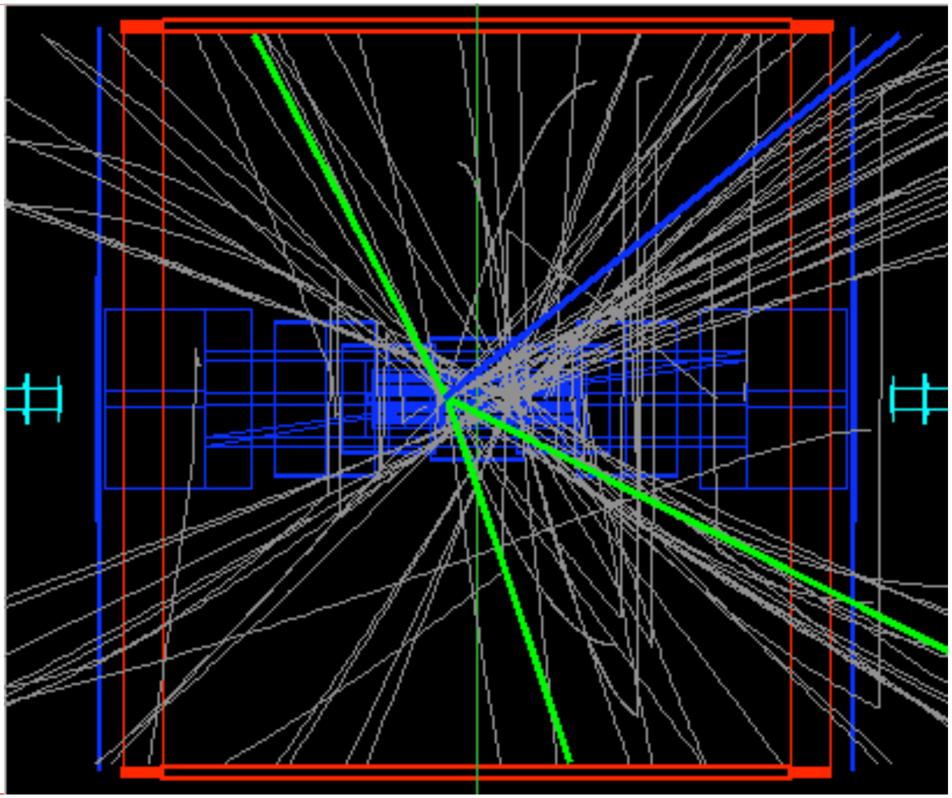

- Separate high and low purity samples to extract maximum sensitivity :

| Category | Candidates without a trackless electron | Candidates with a trackless electron |
|---|---|---|
| $ZZ$ | $1.990 \pm 0.013 \pm 0.210$ | $0.278 \pm 0.005 \pm 0.029$ |
| $Z$+jets | $0.014^{+0.010}_{-0.007} \pm 0.003$ | $0.082^{+0.089}_{-0.060} \pm 0.016$ |
| Total | $2.004^{+0.016}_{-0.015} \pm 0.210$ | $0.360^{+0.089}_{-0.060} \pm 0.033$ |
| **Observed** | **2** | **1** |

# ZZ→llll (CDF)

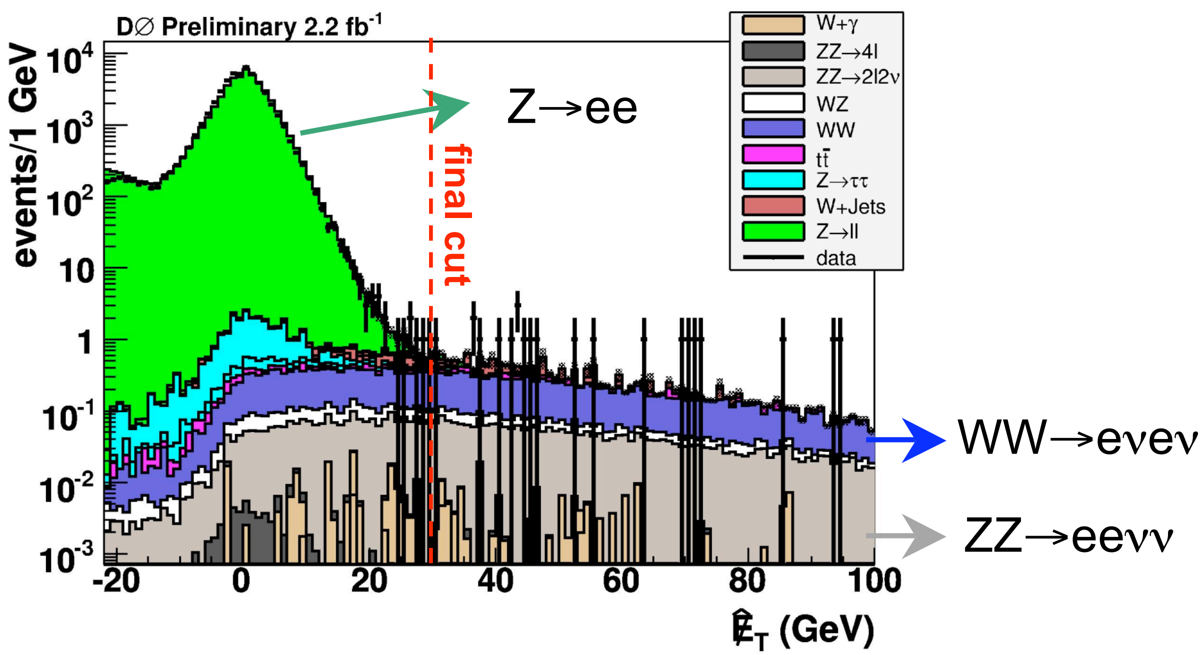
- Example **ZZ→μμμμ** event.
- 3 out of 4 muons missed by muon chambers ! Smart lepton ID essential.



# $ZZ \to ll\nu\nu$ (DØ)

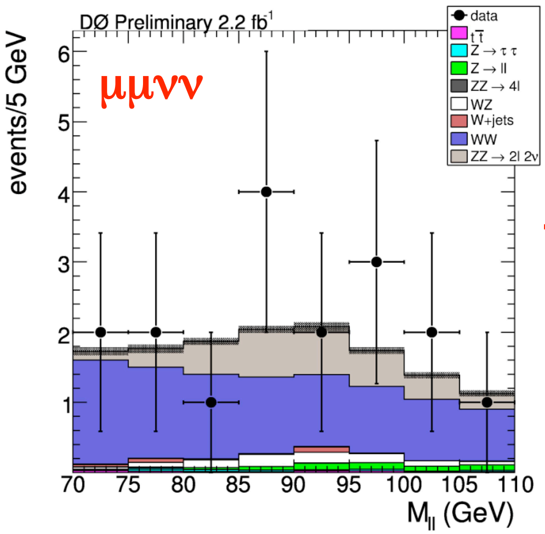
- Recall : BR($ZZ \to ll\nu\nu$) ~ 6 × BR($Z \to llll$).
- But backgrounds are much worse.
- Define a (signed) missing-$E_T$ like object :




▸Most backgrounds removed by requiring missing-$E_T$ be *large* and *significant*.

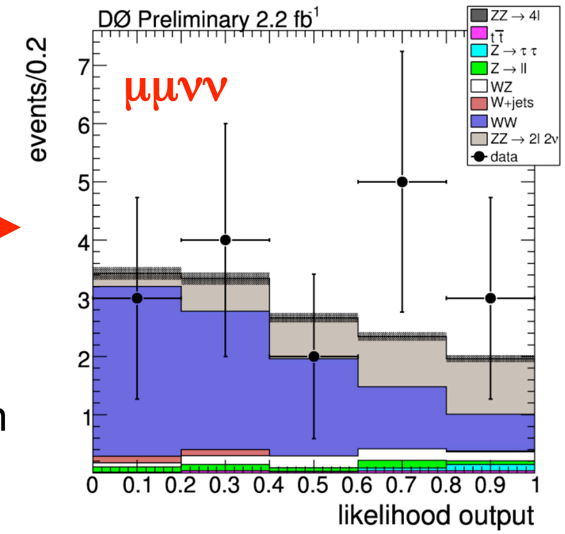
▸The WW background (real missing-$E_T$) can only be separated statistically.

# ZZ→llνν (DØ)




Use kinematic information to form a signal/background likelihood discriminant.

- leading lepton $p_T$
- $l^-$ polar angle in $l^+l^-$ rest-frame
- opening angle between dilepton and leading lepton




- Probability of background alone giving rise to the observed likelihood distribution :

| 2.2 fb$^{-1}$ | eeνν | μμνν | Combined |
|---|---|---|---|
| **p-value** | 0.1140 | 0.0052 | 0.0082 |
| **(expected)** | (0.0753) | (0.1100) | (0.0387) |
| **significance** | 1.21 | 2.57 | 2.40 σ |
| **(expected)** | (1.44) | (1.23) | (1.77) |

**$\sigma(ZZ) = 2.1 \pm 1.1(\text{stat.}) \pm 0.4(\text{syst.})$ pb      $[\sigma_{NLO}(ZZ) = 1.6 \pm 0.1$ pb$]$**

# ZZ→llνν (CDF)

- CDF use *full kinematic information* to try to dig out S/B~20 :

observed lepton 4-momenta and missing-$E_T$

LO theoretical distribution (ME⊗PS)

efficiency function

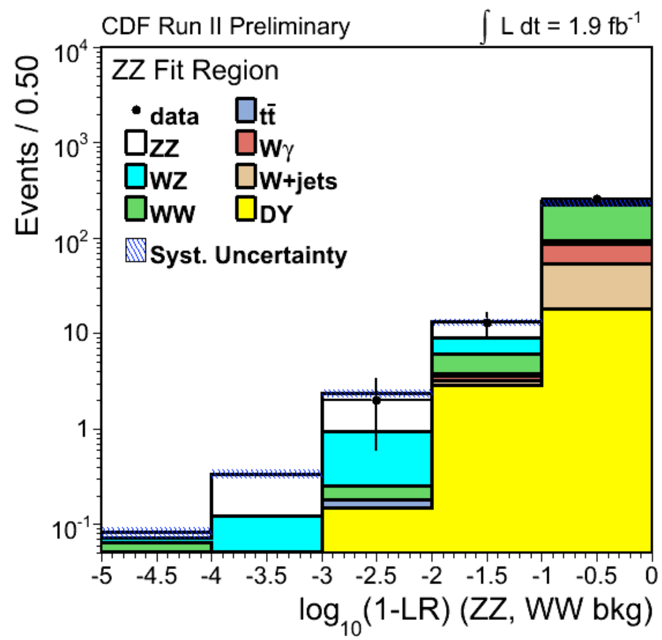
smearing function

true lepton and neutrino 4-momenta

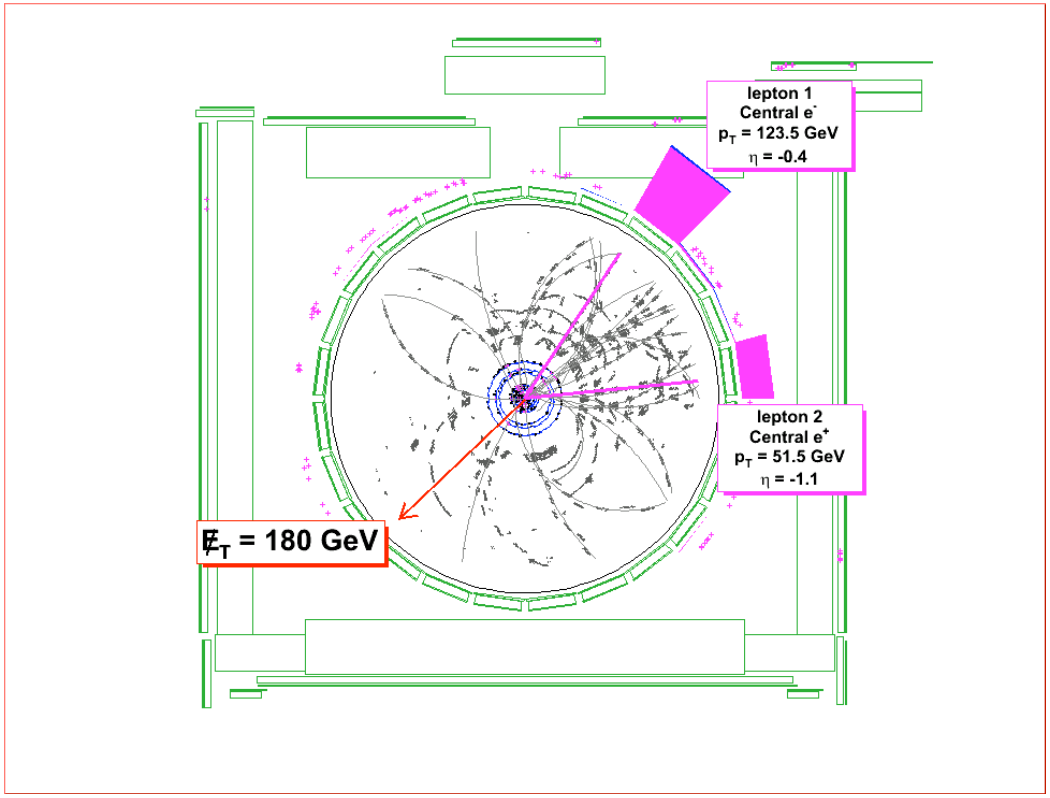
$$P(x_{obs}) = \frac{1}{\langle\sigma\rangle}\int \frac{d\sigma_{LO}(y)}{dy}\epsilon(y)G(x_{obs},y)dy$$

- Discrimination against the dominant background is obtained by forming the likelihood ratio :

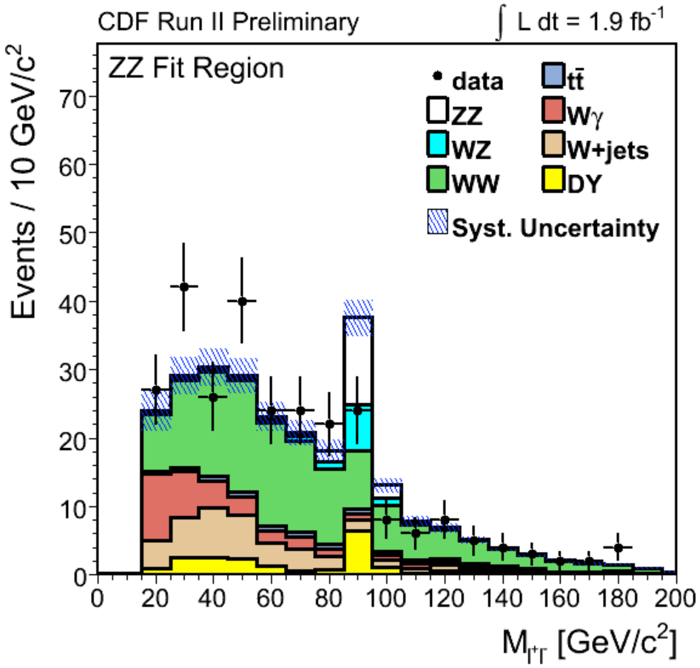
$$LR = \frac{P_{ZZ}}{P_{ZZ} + P_{WW}}$$



# ZZ→llνν (CDF)




- The data contain high probability ZZ events, e.g. ZZ→eeνν shown.
- Probability of background alone describing the data is 0.12 (1.2σ)



# ZZ Combination (CDF)

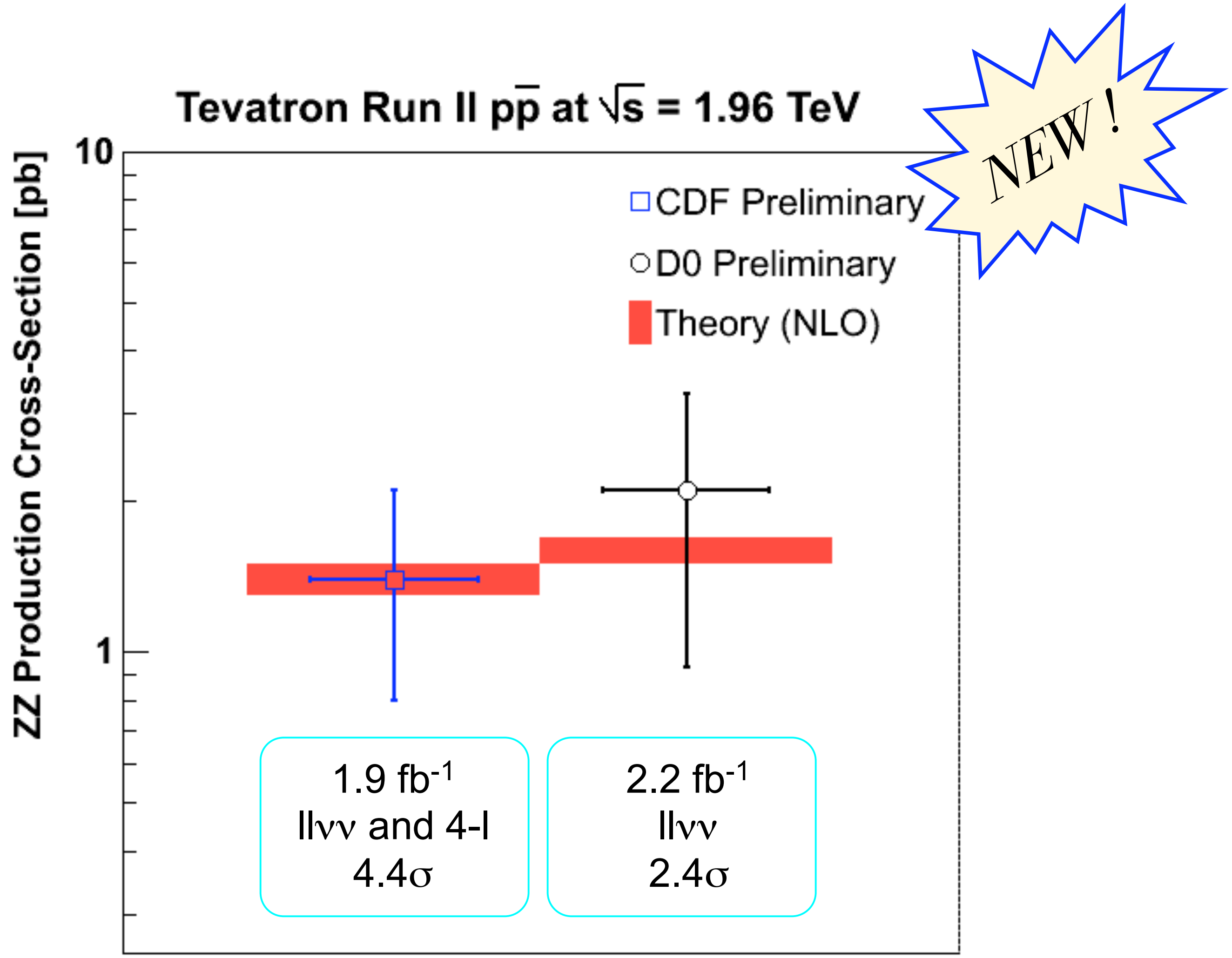
- Extend the likelihood discriminant to include the two (high-purity and lower-purity) 4-lepton measurements :

| 1.9 $fb^{-1}$ | $ll\nu\nu$ | 4-lepton | Combined |
|---|---|---|---|
| **p-value** | 0.12 | $1.1\times10^{-5}$ | $5.1\times10^{-6}$ |
| **significance** | 1.2 | 4.2 | $4.4\ \sigma$ |

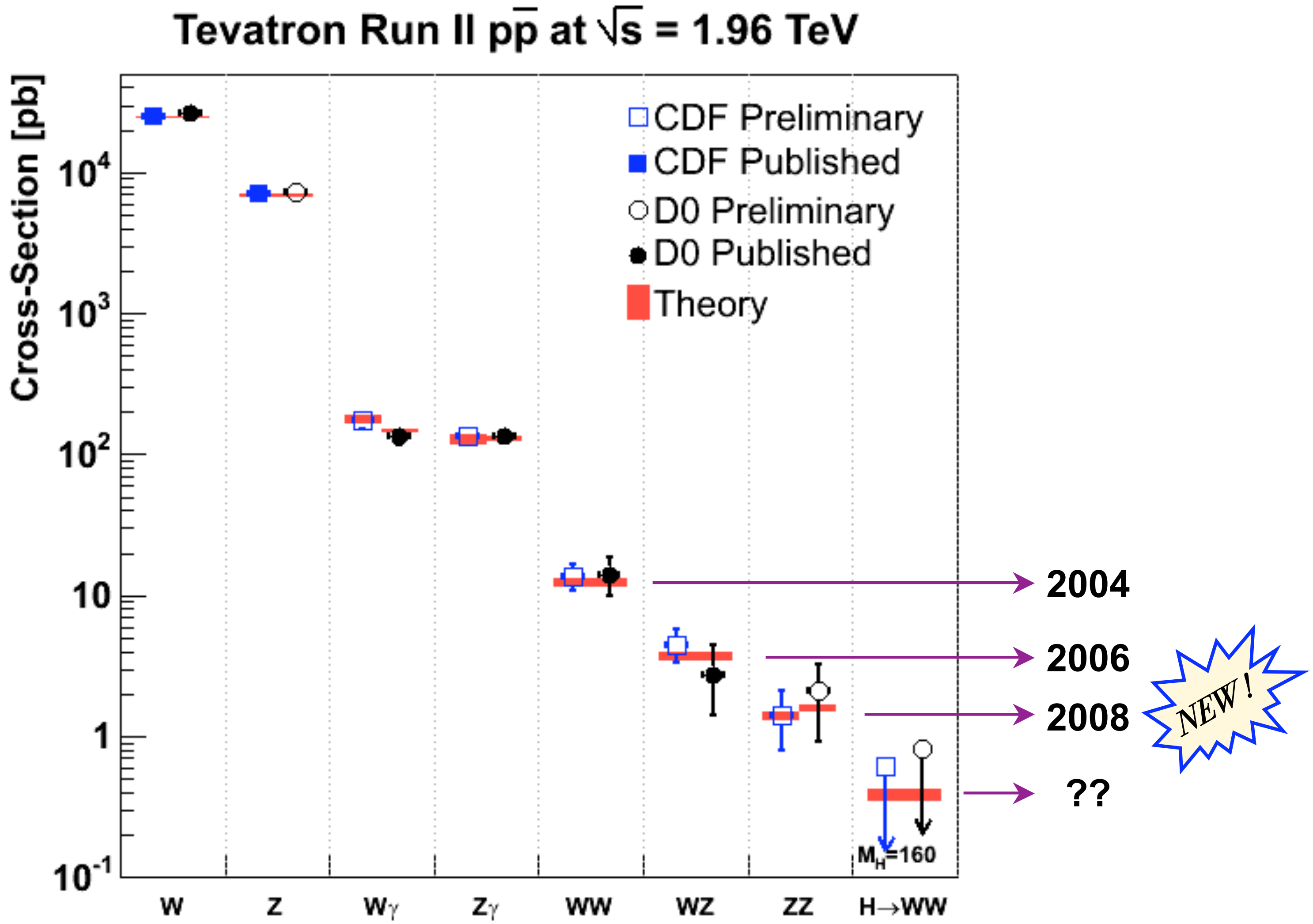
- Expected : 50/50 chance of seeing a $5\sigma$ effect.

**$\sigma(ZZ) = 1.4^{+0.7}_{-0.6}$ (stat. + syst.) pb   [$\sigma_{NLO}(ZZ) = 1.4 \pm 0.1$ pb]**

# ZZ Measurement



# Summary



Tevatron Run II $p\bar{p}$ at $\sqrt{s}$ = 1.96 TeV
Cross-Section [pb]
$10^4$
$10^3$
$10^2$
10
1
$10^{-1}$
CDF Preliminary
CDF Published
D0 Preliminary
D0 Published
Theory
$M_H$=160
W
Z
Wγ
Zγ
WW
WZ
ZZ
H→WW
2004
2006
2008
??
NEW !

*The End*

# Effective Missing-$E_T$ Definition

- Combines elements of *missing-$E_T$* and *missing-$E_T$ significance* :

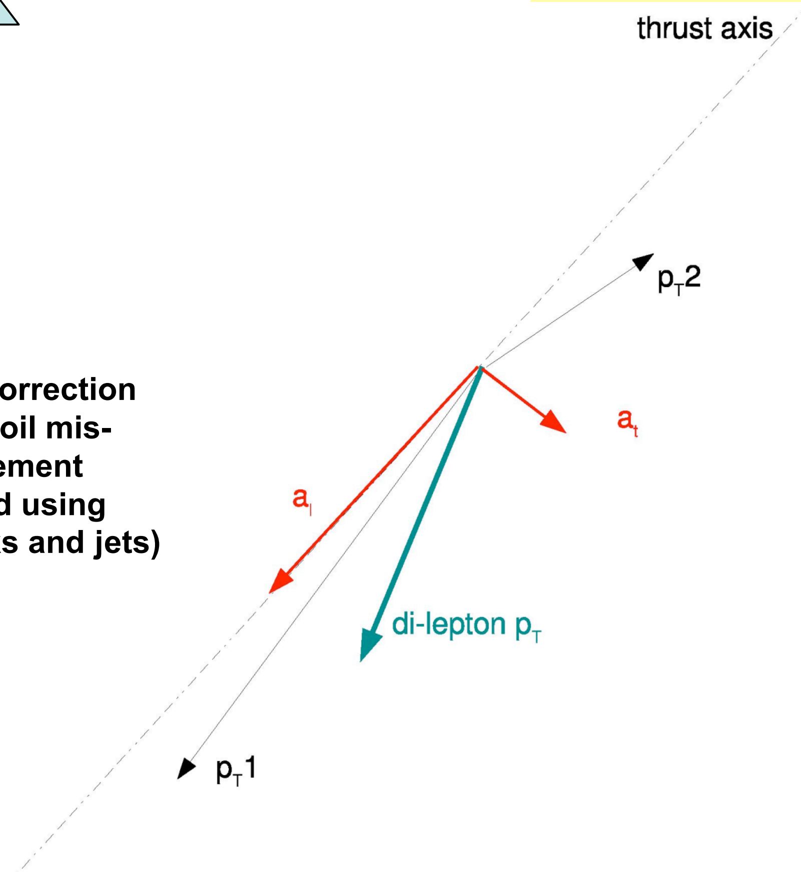
$$\not{E}_T = \sqrt{\not{E}_l^2 + (1.5 \times \not{E}_t)^2} - \delta_m - \delta_{track,\,jets}$$

give extra weight to better measured component

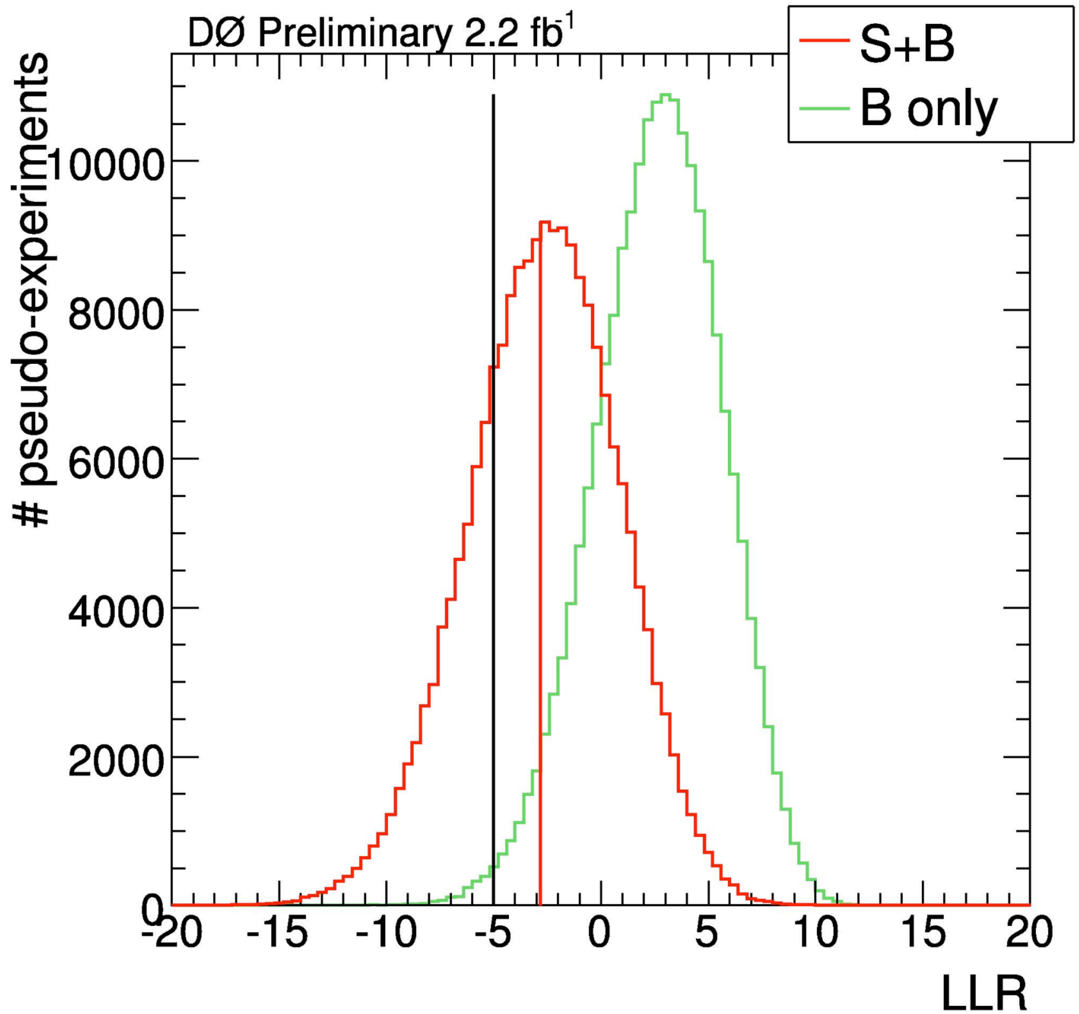
maximum correction due to lepton mis-measurement

maximum correction due to recoil mis-measurement (estimated using leptons tracks and jets)

$$\vec{t} \propto (\vec{p}_T^{\,1} - \vec{p}_T^{\,2})$$

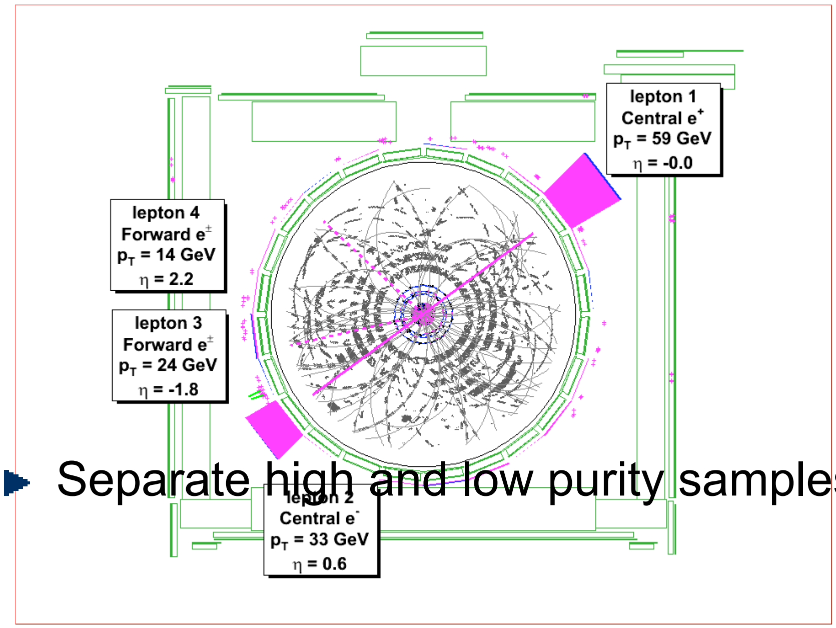


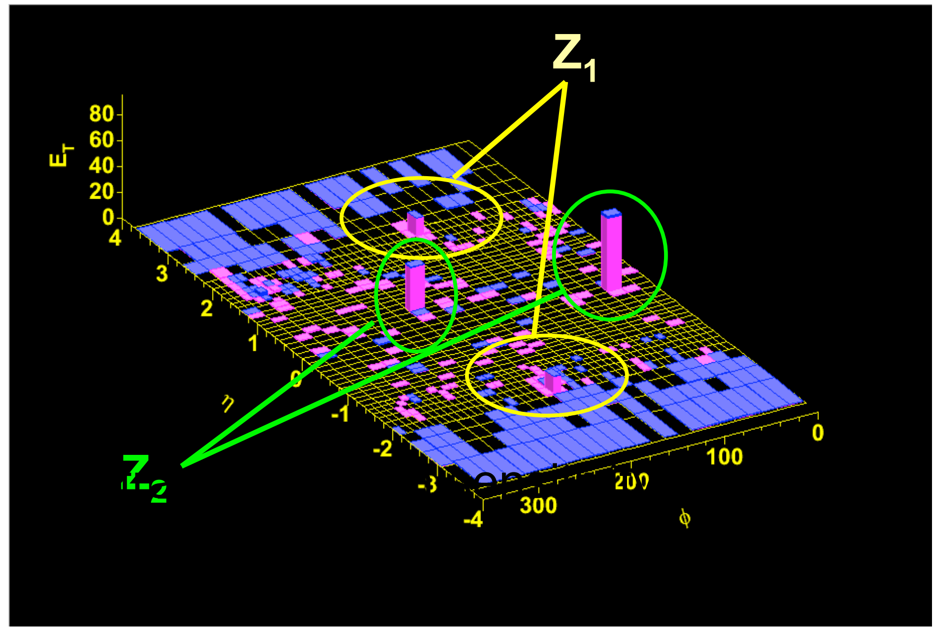
# ZZ→llνν (DØ)



DØ Preliminary 2.2 fb-1
S+B
B only
# pseudo-experiments
0
2000
4000
6000
8000
10000
-20
-15
-10
-5
0
5
10
15
20
LLR

# ZZ→llll (CDF)




- Separate high and low purity samples